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Significant mechanical softening of copper under coupled electric and magnetic stimuli

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ABSTRACT

The mechanical reliability of metallic components is vital for the stable operation of electrical equipment, especially for those used in ultra-high voltage transmission and electromagnetic launching, where metallic materials inevitably suffer from high-density current and strong magnetic field. However, little has been known about the mechanical behavior of metals under the electric-magnetic coupling stimuli. Here, by performing quantitative electromechanical tests under the built-in magnetic field inside transmission electron microscope, we found that copper, one of most commonly used conductive metals, can be significantly softened by the coupled electrical-magnetic stimuli, manifested as notable yield strength drop by five-times and obvious creep deformation at room temperature. A plausible mechanism behind the unusual softening, local-Lorentz-force-assisted dislocations depinning, has been proposed. Our results shed new light on understanding the deformation-induced failure of metals served in electromagnetic environments, and also inspire a new mechanical processing way for reshaping metals at much lower loads and temperatures.

Many key copper components, such as windings of the converter transformer used in the ultra-high voltage (UHV) transmission [1,2] and the rails in the electromagnetic launching [3,4], are inevitably working in the coupled condition of high-density electric current and strong magnetic field. Taking the converter transformers of UHV transmission for example, the electric current density through copper during the short-circuit that occurs from time to time can reach 10^4 A/cm^2 or higher [5] (this value even reaches 10^6 A/cm^2 for electromagnetic launching [6]), and the induced magnetic field is as strong as several tesla (T). Coppers working in this condition always have an undesirable mechanical deformation, which may cause the premature failure or even total loss of the whole equipment [7]. In recent years, great efforts have been made to study the effect of individual electric [8–10] or magnetic stimuli [11–13] on the mechanical deformation of metallic materials. However, little has been known about the mechanical behaviors of conductive materials under the concurrent electric and magnetic stimuli, especially from the quantitative aspect, given the complexity of multi-fields coupling tests.

By virtue of the strong built-in magnetic field inside transmission electron microscope (TEM) equipped with the in-situ electro-mechanical technology [14–17], we have established a quantitative electro-magnetic-mechanical testing system. Using this design, it's possible to load a sample with high-density current, visualize the deformation process, and meanwhile obtain the corresponding load-displacement curve under magnetic fields. Here, magnetic fields with two different intensities (~0.02 T at low and ~2 T at high magnification mode) exist in the TEM [16,18], which provides a static and uniform magnetic environment for microscale samples. Taking advantage of the established quantitative electro-magnetic-mechanical experimental setup, we found a dramatic softening of copper pillars under the coupled electric pulse and magnetic stimuli at room temperature: the yield strength drops by five times when a ~10^6 A/cm^2 electric pulse and the ~2 T magnetic field are concurrently imposed. The local Lorentz force-assisted dislocations depinning from tangled configurations has been proposed as a plausible mechanism for the significant mechanical softening.

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The copper samples used here were directly taken from a UHV transmission cable core (Fig. 1a), which was made by the oxygen-free high-purity (>99.95 wt.%) copper via cold-working. The inset in Fig. 1a exhibits electron backscattering diffraction (EBSD) mapping results of selected areas of the cable, demonstrating an average grain size of ~5.3 μm. High-density tangled preexisting dislocations introduced by cold-working can be clearly observed (see the TEM image taken under dual-beam conditions in Fig. 1b). The dislocation density was estimated to be 5.96×10^{14} m^{-2} using the line intercept method [19].

Copper plates were wire-cut from the cable and mechanically grinded to the thickness of ~100 μm, followed by electrochemical etching of one edge to <50 μm. Submicron-sized copper pillars with side length of ~500 nm and axial length of ~1500 nm were fabricated on the thinned edge via a focused ion beam (FIB, FEI Helios NanoLab 600i) using 30 keV Ga^{+} with gradually decreased beam current from 9.3 nA to 28 pA. Specifically, copper pillars were carefully machined by selecting areas inside individual grains through the orientation-dependent imaging of the ion beam (**Supplementary Fig. 1**). Quantitative compression tests with electric pulses were performed via an electro-mechanical coupling holder (Bruker-Hysitron PI 95 ECR) under the built-in magnetic field inside a 200 kV field-emission gun TEM (JEOL-2100F), see **Supplementary Fig. 2**. As shown in Fig. 1c, upon the tungsten punch well-touched with pillars, the mechanical load (***F***, the white arrow) and electric pulses (***i***, blue pulses) can be simultaneously applied to the sample exposed in the magnetic field (***B***, black crosses). Fig. 1b exhibits schematic illustrations of the loading curve with a constant displacement rate and electric pulses. Periodic electric pulses with square profile were applied via a source meter (Keithley 2602A) controlled by software. The width of electric pulses was set as 0.07 ms during a pulse period of 100 ms, to minimize the Joule heating effect. Note that electric pulses were artificially turned off before the unloading, therefore the real-time deformation behaviors of the pillars with and without electric pulses can be clearly observed and recorded.

Typical engineering stress-strain curves of copper pillars compressed with or without electric pulses under 0.02 and 2 T magnetic fields are shown in Fig. 2. As exhibited in Fig. 2a, the uncharged copper pillars in 0.02 T magnetic field demonstrate the yield stress of ~300 MPa and intermittent strain during the plastic flow, manifested as the individual strain bursts. Here, the yield stress was defined as the onset of the first strain burst, or the point deviating from linear elasticity. When subjected to electric pulses of 6.9×10^{6} A/cm^{2} under a 0.02 T magnetic field, no apparent changes were observed in the deformation behavior, yield stress or flow stress of the copper pillar with the power on and off. As displayed in Fig. 2b, for the uncharged pillars in the magnetic field with the increased intensity of 2 T, they demonstrate similar deformation way and strength with the low-magnetic field cases. However, when electric pulses of $\sim10^{6}$ A/cm^{2} passes the sample in the 2 T magnetic field, copper pillars readily deform at lower stresses. Blue part of the curves in Fig. 2b exhibit the sample deformation with different current density, one can find both the yielding and the subsequent plastic flow stress already occurred and sustained at reduced stress level. And the higher current density results in lower yielding and flow stress. Interestingly, once the electric power was cut off, the flow stress can recover to the normal value (~500 MPa) immediately. The above experimental results indicate that the dramatic decrease of yield and flow stress in copper occurred with the concurrent 2 T magnetic field and 10^{6} A/cm^{2} electric pulses, resulting in a significant "electromagnetic softening".

To more clearly illustrate the softening degree of copper pillars charged with different electric current density in magnetic fields, the yield stress and normalized stress recovery upon power off were

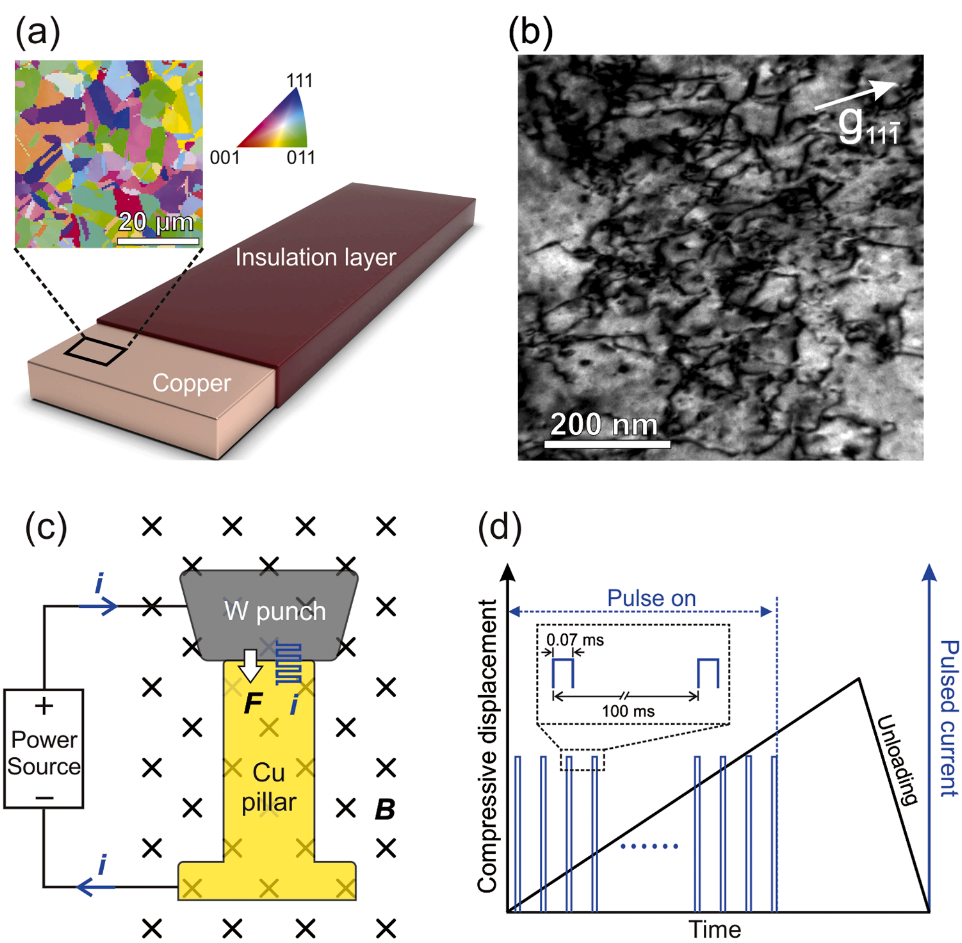

Fig. 1. (a) The schematic illustration of the copper cable sample and the EBSD mapping of a local area. **(b)** A typical bright-field TEM image showing the dislocation configurations in the cold-worked copper sample with the ***g*** vector of the dual-beam condition labeled upper right. **(c)** The schematic of the in-situ electromechanical test under a static magnetic field inside TEM. ***F, B*** and ***i*** indicated the mechanical load, magnetic field and electric pulses, respectively. **(d)** The schematic of compressive loading with constant displacement rate coupled with electric pulses. Note that the electric pulses have been cut off before unloading. The inset dashed rectangles show detailed parameters of electric pulses.

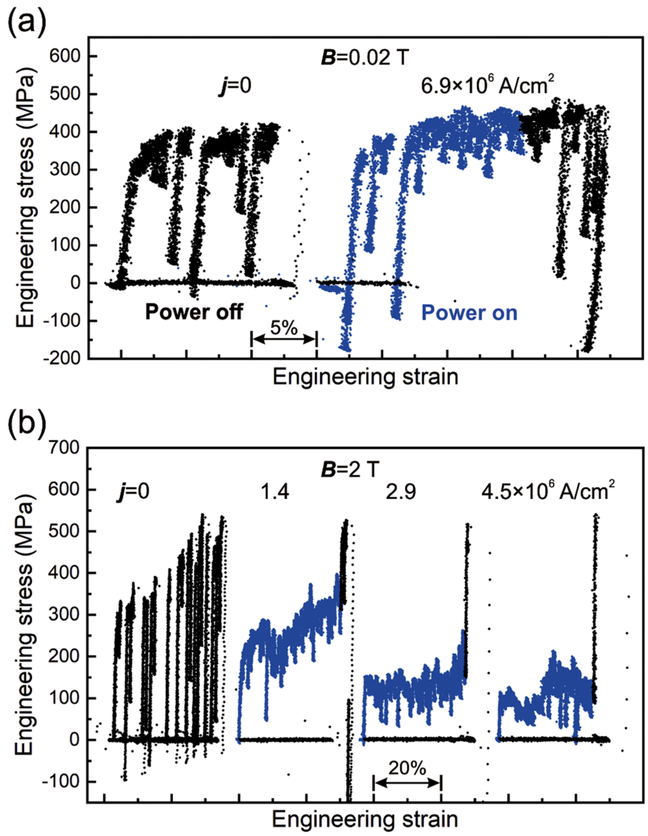

Fig. 2. **(a)** Typical engineering stress-strain curves of the copper pillar compressed under 0.02 T magnetic field without and with electric pulses of 6.9 × 10^6 A/cm^2. **(b)** Typical engineering stress-strain curves of the copper pillar compressed under 2 T magnetic field without current, with electric pulses of 1.4 × 10^6 A/cm^2, 2.9 × 10^6 A/cm^2 and 4.5 × 10^6 A/cm^2. The power-on part of the curves is highlighted by blue color.

measured as a function of current densities in the 2 T and 0.02 T magnetic fields, respectively. Copper pillars compressed in the 2 T magnetic field without pulse current through, hold the yield strength in the range of 240 ∼ 310 MPa (Fig. 3a). When the pulse current density reaches to 7.4 × 10^6 A/cm^2, the yield strength decreases down to ∼54 MPa, i.e., the higher current density corresponds to the much lower yield strength. While for the 0.02 T magnetic field case, the yield strength remains almost constant (∼320 MPa) with the increasing current density. Normalized stress recovery after power-off is defined as ($\sigma_{power\text{-}off}$ - $\sigma_{power\text{-}on}$)/$\sigma_{power\text{-}off}$, where the $\sigma_{power\text{-}on}$ and $\sigma_{power\text{-}off}$ stands for the instantaneous stress of deformed samples before power-off and the achievable highest stress after power-off, respectively, as schematically illustrated in the inset of Fig. 3b. Similar with the yield strength change, in the 2 T magnetic field: the higher current density, the larger stress recovery upon power-off; whereas in the 0.02 T magnetic field, no detectable stress recovery when power off, even copper pillars have been charged with much higher current densities. This suggests that the electromagnetic softening is tunable with a suitable combination of the current density and magnetic field intensity.

Specifically, to further evaluate the time-dependent deformation behaviors in copper under coupled electromagnetic stimuli, the "electromagnetic creep" tests were carried out inside TEM. The schematic experimental setup is illustrated in Fig. 4a. A constant mechanical force was applied and maintained, under which the copper pillar is far from yielding. Then the elastically-loaded copper pillar was imposed with electric pulses under the 2 T magnetic for 60 s, during which the pillar became shortened gradually. The TEM images of a copper pillar before and after the "electromagnetic creep" test (Fig. 4b) show obvious plastic deformation. The axial length change $\boldsymbol{\Delta L}$ of each copper pillar was carefully measured via the pixel analysis to assess the accumulated creep strain, defined as $\boldsymbol{\varepsilon_c} = \boldsymbol{\Delta L/L_0}$, where $\boldsymbol{L_0}$ is the initial axial length of the pillar. Fig. 4c demonstrates the accumulated creep strain $\boldsymbol{\varepsilon_c}$ in different magneto-electro-mechanical test combinations. In the 2 T magnetic field, the copper pillar will have larger $\boldsymbol{\varepsilon_c}$ with the applied mechanical force or pulse current density increased, and the maximum $\boldsymbol{\varepsilon_c}$ is as high as 50.8% in our experiments. In contrast, under the same mechanical load, $\boldsymbol{\varepsilon_c}$ is close to zero for those copper pillars tested in 0.02 T magnetic field even with higher pulse current density (7.5 × 10^6 A/cm^2). The "electromagnetic creep" experiment results further validate that the strong enough electric and magnetic coupled stimuli can make the copper pillar deform permanently with the applied force well-below the yielding, and the room-temperature accumulated creep strain is surprisingly large in a quite short exposure time (only 60 s).

To understand the unusually significant "electromagnetic softening" in copper, the major contributing factors should be found out. The plastic deformation of the tested copper with the diameter of ∼500 nm is mediated by the dislocations sliding [20]. Therefore, the contributing factors for the observed softening should be what can affect the dislocation activities in metals. For the coupled electro-magneto-mechanical case here, the known mechanisms that may facilitate the motion of dislocations are the Joule heating effect [10,21], electron wind force

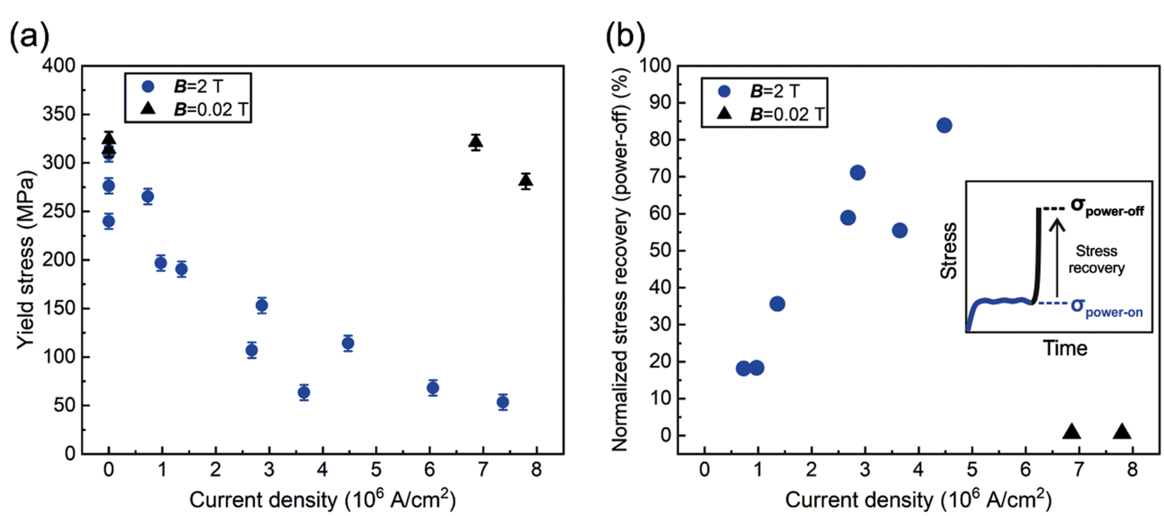

Fig. 3. The yield stress **(a)** and normalized stress recovery upon power-off **(b)** as a function of the current densities under the 0.02 and 2 T magnetic field, respectively. The inset in **(b)** show the schematic of stress recovery upon power off in the 2 T magnetic field.

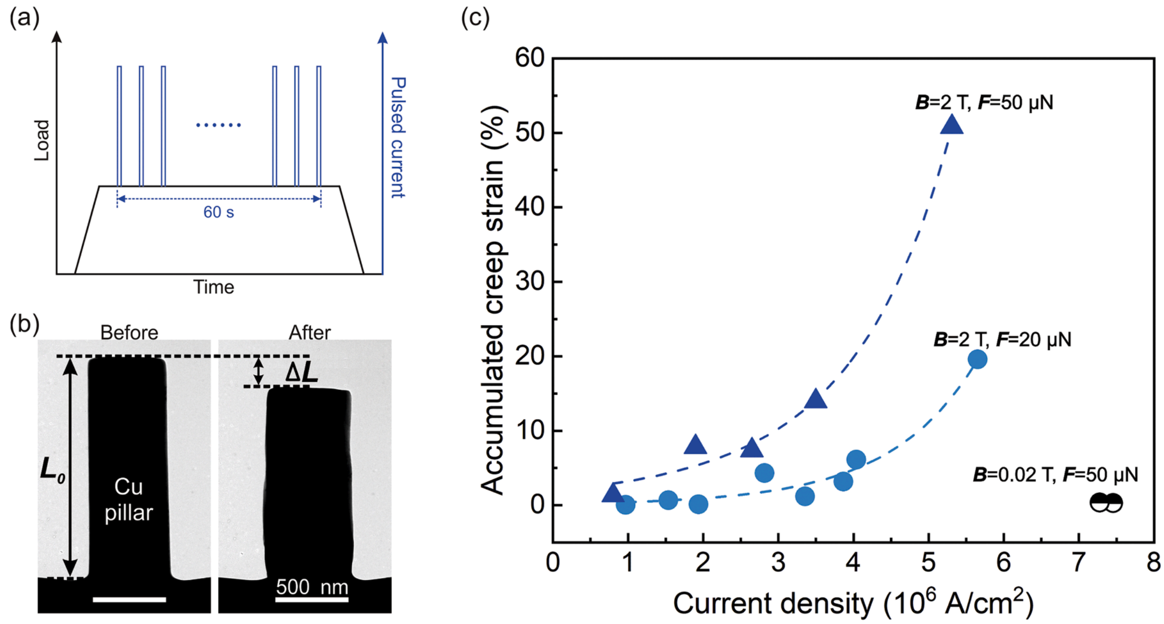

Fig. 4. (a) The schematic curve of the creep test under the load-control mode coupled with electric pulses. Notice that electric pulses were imposed within the constant loading range. **(b)** TEM images of a typical submicron copper pillar before and after the creep test under the applied load of 50 μN coupled with electric pulses of 3.5 × 10^6 A/cm^2 and magnetic field of 2 T. **(c)** The accumulated creep strain of submicron copper pillars with respect to current densities under magnetic fields of 2 T and 0.02 T, respectively, with detailed experimental parameters shown next to the symbols. Dash lines exhibit the numerical fitting.

[22] as well as the magneto-plasticity effect [23].

The dominant effect of Joule heating for the observed softening can be excluded firstly, since the mechanical softening does not occur in the absence of the strong enough magnetic field (2 T), even though the current density reaches as high as ~7 × 10^6 A/cm^2 (Fig. 2a). Similar compression tests were performed on copper pillars charged by the continuous current of 10^6 A/cm^2 under the weak magnetic field (0.02 T), where the Joule heating effect is more pronounced than the pulse current cases, but no mechanical softening observed, either (**Supplementary Fig. 3**). In addition, the temperature increase caused by Joule heating in copper has been estimated via the finite element modeling using the COMSOL Multiphysics software with identical sample dimensions. The simulation results show a negligible temperature rise of only less than 0.5 K (**Supplementary Fig. 4**), primarily due to the rapid thermal energy dissipation via the heat conduction to heat dissipaters, such as the millimeter-sized copper substrate and tungsten tip, copper mount, and the metallic components of the TEM holder.

The electron wind force, resulting from the momentum transfer from drift electrons to metal atoms, can promote the mobility of dislocations to some extent [24]. If the electron wind force is the dominant factor, similarly, the mechanical softening should not rely on the applied strong enough magnetic field but be closely related to the electric current density. Actually, no apparent softening has been observed in copper pillars compressed under the weak magnetic field (0.02 T) regardless of the current density, pulse or constant current (**Supplementary Fig. 3**). The electron wind force, σ_{ed}, can be estimated according to the equitation $\sigma_{ed} = C_{ew} j$, where C_{ew} is the electron force coefficient as 2.95×10^{-6} MPa/(A/cm^2) for copper [10]. With the current density of 6.9 × 10^6 A/cm^2, the calculated σ_{ed} is only ~20 MPa, far below the stress (~10^2 MPa [25]) for driving dislocations in submicron pillars of face-centered-cubic metals. Therefore, the electron wind force is not the critical factor, either.

Magneto-plasticity theory argues that the pulse current-induced [26] or the external magnetic field [11–13] may assist dislocations depinning from the paramagnetic obstacles and hence make the plastic deformation of metallic materials easier [13,27,28]. However, the reported magnetic effect theory was more applicable for metals with a considerable quantity of solute atoms or particle inclusions [29]. Whereas, the copper materials studied here are simple metals with high purity. Therefore, the magnetic-field-assisted depinning of dislocations from paramagnetic obstacles should not be dominant to the softening here.

According to the discussion above and our experimental results, individual electric pulses or magnetic field cannot instigate the unusually significant softening in the coupled electro-magneto-mechanical condition. A plausible mechanism of local-Lorentz-force assisted depinning of tangled dislocations is naturally proposed. Before or during the plastic deformation, dislocations interact with each other and form the immobile dislocation tangle configuration. These dislocation tangles cannot be untied until the applied load increases to a high enough value, followed by collective dislocations gliding out of the sample quite easily and reconstruction of the tangled structure again in the subsequent deformation [25,30]. So, the depinning of dislocations becomes the rate-limiting process in the plastic deformation of submicron-sized copper pillars. Multiple dislocation junctions in the tangled dislocation network act as effective pinning points of dislocation, meanwhile these pinning points with more disordered lattice would severely scatter drift electrons, enabling local high-density electrons near pinning points [29,31]. Once the electrons begin to move, even by a small distance, a local Lorentz force near pinning points would be produced in the magnetic field. When the magnetic field is strong enough (e.g., ~2 T), the induced local Lorentz force will hence be large enough to depin dislocations with the assistance of a much lower externally applied mechanical loading, i.e. the "electromagnetic softening". Higher current density means more local electrons and hence the larger local Lorentz force, therefore the pillars would yield at a lower mechanical stress.

To recapitulate, making full use of the built-in magnetic field inside TEM, we performed a series of in-situ electro-magneto-mechanical tests and found an unusual mechanical softening in copper. This "electromagnetic softening" is much more significant than the known electroplasticity [32,33] or magnetoplasticity [13], and can be well tuned with a suitable combination of the current density and magnetic field intensity. This finding would be helpful to understand the premature failure of some metallic components served in engineering converter transformers of the UHV transmission, i.e., these metals with originally high-enough design strength become much softer and deform with larger and larger plastic strain with the extension of service time. What's more, our finding may inspire a new processing method, given that metals can be significantly softened to dramatically lower stress level with no extra heating requirement and apparent temperature increase, avoiding the coarsened crystals and reducing the energy consumption.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scriptamat.2023.115438.

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